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Ultrasound-assisted handling force reduction during the solar silicon wafers production

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ABSTRACT

Surface adhesion between wet wafers poses great challenges for silicon wafer handling. It has been shown that both the shear and normal handling forces of the solar silicon wafers can be dramatically reduced by using the ultrasound energy. Approximately 20 and 5 times reduction in horizontal and vertical forces were achieved by as low power as 10 W, and a good agreement was found between the measured values and the predictions of a simple model for the effect of longitudinal vibration we developed.

1. Introduction

Currently more than 80% of all commercial solar cells are made of silicon [1]. The need to increase the efficiency and lower the cost of silicon wafers promotes the use of thinner and larger wafers [2]. However, recent industrial studies have shown that the use of thinner wafers can lead to unacceptable yields arising from wafer and cell breakage due to handling, transport and/or processing during solar cell production [3,4]. Since about 40–60% of the total cost is due to fabrication of the silicon wafer, safe handling is an important issue [5].

Suction process is the most common (and critical step for breakage) process in the handling of silicon wafers. It is very desirable for industry due to the breakage reduction of silicon wafers if suction force is reduced somehow. The vacuum pressure of suction cups (suction force) is proportional to the adhesion force between wet wafer (due to wafer singulation) and support. Therefore, reduction in adhesion force could be interesting to be concentrated on. Vibration can be a good candidate to reduce the adhesion force. In fact, static friction coefficient converts to the dynamic friction coefficient which is much smaller than static one.

Friction process with vibration is an important phenomenon because the influence of vibration can cause significant change in the friction process. Some studies [6–16] have found that vibration can reduce friction. It has been shown that both mean friction force and wear rate increase or decrease depending on the vibration parameters [17,18]. Several studies [19–23] observed that the reduction of friction force depends on roughness of the rubbing surfaces, relative motion, type of material, temperature, normal force, stick slip, relative humidity, lubrication and vibration. Among these factors normal load and sliding velocity are the two major factors that determine the variation of friction [24]. It was reported [25–28] that friction coefficient of metals and alloys varies under different operating conditions. Other studies have found that vibration can reduce wear (reduction in friction). They have shown that micro-vibrations (10–100 μm amplitude) can reduce sliding wear up to 50% [29–37]. Recently, high power ultrasound (frequency up to 100 kHz and high amplitude 100 μm) have been used to control friction in metal working [38–43], wire drawing [44–47], and cutting [48–50].

The sticking force between contacting wet surfaces can be manipulated by ultrasound. However, this technique of silicon wafer handling has not yet been investigated. Hence, the main contribution of this paper is the development of a safe handling methodology by using ultrasound energy. A simple analytical model is proposed to show that using ultrasound can reduce the sticking force. Experiments are also performed to verify the proposed approach. The results of the theoretical investigations and the experiments show good agreement.

2. Theory

Friction issue falls into two categories: contact scenario and friction mechanisms. The first category of friction issue consists of the asperity interaction scenario itself. This scenario only

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considers the normal distance between asperities of both surfaces as a function of the relative horizontal translation between them. The second category discusses the mechanisms governing friction: creep, adhesion and geometrical deformation of asperities.

2.1. Contact scenario

On the microscopic level, smooth surfaces seem "rough." The surface topography plays an important role in surface interactions. When these surfaces are pressed against each other, the true contact area usually is from 1/400 to 1/10,000 of the apparent area observed by the naked eye. The protuberant features are called asperities. One of the oldest and simplest micro-contact models is the Greenwood–Williamson model [51], which assumed that surfaces were composed of hemi-spherically tipped asperities. The asperities assume by a uniform sphere and a symmetrical Gaussian distribution of asperity heights. The Hertz equations governing elastic contact of spheres and half spaces are utilized to calculate the load, contact area, and contact pressure acting on a deformed asperity.

The contact scenario is illustrated schematically in Fig. 1. Fig. 1A shows two rough objects in contact together, at their surfaces, while the dashed line presents the upper object translated horizontally to the left over a certain distance. As a result, some asperity contacts will persist (*a* and *d*), some will disappear (*b* and *e*) and new ones will occur (*c*). The normal distance between the two contacting surfaces can also be transformed to one flat surface and one rough surface (Fig. 1B). Fig. 1C shows the equivalent asperity, of contact point *a*, for four different time instances of its lifecycle. An overlap between the two surfaces corresponds to a contact between the two asperities [52].

Asperities of the surface increases by using external high frequency vibration and the real contact area reduces between vibrating surfaces [53–55]. In fact, vibration amplitude adds to the existence asperities at the interface. Also, Velocity-weakening of kinetic friction akin to the Stribeck effect in lubricated contacts, is the phenomenon of decreasing friction force with increasing sliding velocities, (or, in more simplified treatments, the assumption that kinetic friction be lower than static friction, both values being assumed constant). Hence, the friction force tends to be reduced under external high frequency vibration.

2.2. Friction mechanisms

2.2.1. Formulation of the model-contact scenario with the friction mechanisms

The contact surfaces of two blocks rubbing against each other (see Fig. 2A) can be represented by a flexible surface containing all the possible equivalent asperity contacts, each with its own equivalent stiffness, mass and shape depending on the characteristics of the two corresponding interlocking asperities. Each possible equivalent asperity contact has its own individual rigid, shaped lower surface. Fig. 2B shows the life cycle of one such equivalent asperity, where it is assumed that the upper surface is moving from left to right with respect to the fixed lower surface. Topographical characteristics are assigned to both surfaces. The equivalent characteristics of the two interacting asperities (namely stiffness, mass, compression and adhesion) are lumped into one point (•), for simplicity of treatment. This point (Fig. 2B) is initially moving freely (i), until it touches the lower rigid surface (ii), after sticking to and then slipping over the lower profile it breaks completely loose from the lower profile (iii). In case (ii) the asperity is called to be in an active state, for the other cases the asperity is called to be inactive. (This may be reminiscent of the Tomlinson–Prandtl atomic model, except that it accounts for creep, adhesion and load-carrying, which prove essential in revealing friction force dynamics). In this case, we have ignored the possible vibrations of a contacting asperity.

From the moment the asperity becomes active, it will begin to follow the profile of the lower surface, by deforming normally ς and tangentially ξ, resulting in a normal and tangential force. The normal force, $F_n(t)$, is given by $k_n{\cdot}\varsigma(t){\cdot}f(\xi)$, where k_n is the normal

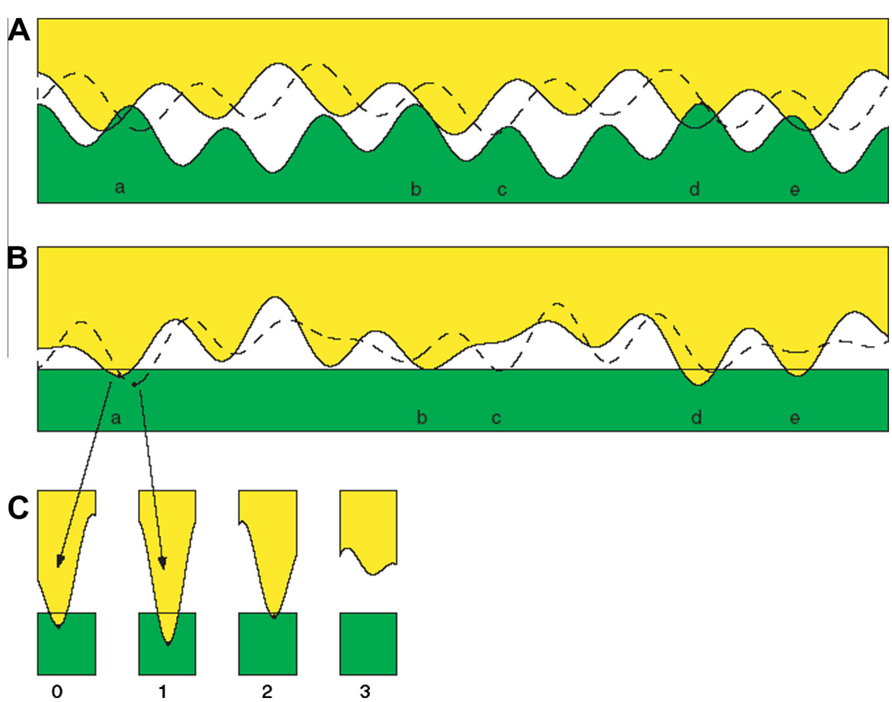

Fig. 1. A schematic representation of friction mechanism. The upper figure shows two surfaces in sliding contact with each other. The dotted line corresponds to the upper surface shifted to the right over a certain distance. The middle figure shows the transformation of the upper figure where the lower surface becomes a flat surface (note the different shape for the shifted surface). The lower figure shows the transformed surfaces of point a for four different shift values. The first and the second one correspond to the full and dotted lines in the middle figure [52].